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**6. AUTHOR(S)**
Ilia Zolotov

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Oregon State University
Corvallis, OR 97331

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Successful inversions of nephelometer data into the aerosol particle size distributions by the method of mean ordinates [1] encouraged us to apply this method to the data on the oceanic volume scattering function (VSF) obtained during LEO-15 Experiment. The objective of this work is to study the potentials of the method of mean ordinates to invert VSF into the particle size distribution (PSD) of oceanic hydrosol in coastal zones (zones of intense scattering). The inversion of VSF by the method of mean ordinates was applied both to numerical experiments and to VSF data obtained during LEO-15 Experiment.

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# The Determination Of The Aerosol Microphysical Characteristics In The Lower Part Of The Marine Atmospheric Boundary Layer From Lidar Data And Accompanying Measurements

Ilia G. Zolotov
Oregon State University
College of Oceanic and Atmospheric Sciences
104 COAS Administration Building
Corvallis, OR 97331-5503
Phone: (541) 737-5220; fax: (541) 737-2064; email: zolotov@coas.oregonstate.edu
WEBPAGE: http://www.coas.oregonstate.edu/people/zolotov/index.html

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## LONG-TERM GOALS

The long-term goal is to create a microphysical model of marine suspension in the coastal oceanic zone from observations over the volume scattering function.

## OBJECTIVES

Successful inversions of nephelometer data into the aerosol particle size distributions by the method of mean ordinates [1] encouraged us to apply this method to the data on the oceanic volume scattering function (VSF) obtained during LEO-15 Experiment. The objective of this work is to study the potentials of the method of mean ordinates to invert VSF into the particle size distribution (PSD) of oceanic hydrosol in coastal zones (zones of intense scattering). The inversion of VSF by the method of mean ordinates was applied both to numerical experiments and to VSF data obtained during LEO-15 Experiment.

## APPROACH

The difference between this study and currently active investigations to restore oceanic hydrosol structure consists of using all information available in experimental VSFs. The other approaches use either forwardly scattered part of VSF [2,3], or integral properties of VSF such as backscattering and beam scattering coefficients [4], or spectral characteristics of these properties obtained either *in situ*, or by remote sensing [5]. The utilization of complete angular structure of VSF in the angular range between very small forward angles to the angles in backward direction potentially allows us to reveal a complete size distribution structure of different hydrosol fractions starting from distribution of small particles with the sizes less than 1 μm to the lager fractions of organic and inorganic particles such as phytoplankton, clays, and sand particles suspended by water motion. The procedure to invert a full angular scaled VSF into a particle size distribution was widely utilized in atmospheric optics but never successfully employed in marine optics primarily due to the computational difficulties related to the extremely anisotropic nature of marine VSFs.

It is well known that the structure of marine hydrosol is optically very complex [6]. Simplified models are commonly used for practical calculations of light scattering in ocean water. In most cases suspended particles are considered to be homogenous, independently scattering spheres with low absorption in the visible range. Particles of biological origin have relative refractive indices in the range of 1.02-1.005; and terrigeneous particles - in the range of 1.13-1.17.

Our approach to determine the particle size distribution (PSD) of oceanic hydrosol will be based on our method of mean ordinates [7, 8] to invert optical data into microphysical properties of a medium. The method was developed for low-accuracy initial data. In particular, this could be applied to the case of turbid waters. The method involves a quasi-stochastic solution to an inverse problem. Its utilization requires some *a priori* assumptions about characteristics of suspended particles, including the number of hydrosol components, the value of the complex refractive index of each component, and, finally, the particle size interval of each component. Starting with these assumptions, a set of models is created for each component. An ensemble of initial PSD of ocean hydrosol is constructed by combining models of two sets in all possible ways. Each constructed model of the ensemble is tested for conformity to the experimental data: the VSF of each model is calculated using Mie equations and is compared with the experimental VSF. The PSD of ocean hydrosol model is considered acceptable if the relative difference between the calculated and measured VSF does not exceed a certain value which is proportional to the experimental error. In this manner, an ensemble of all acceptable models is constructed. From the ensemble, the mean curve of the particle size distribution (curve of mean ordinates) is computed. Finally, the distribution curve that is the closest to the curve of mean ordinates is selected from the ensemble. This is the particle size distribution that is chosen as the solution to the inverse problem.

## WORK COMPLETED

The inversion of VSF by the method of mean ordinates was applied both to numerical experiments and to VSF data obtained during LEO-15 Experiment.The measurements were carried out in the coastal waters of New Jersey and in the Mexican Gulf with a new Volume Scattered Meter [9] for angles from 0.6° to 177.6° with a step of 0.3°. The results were summarized in tables [10] for 36 angles, which is enough to describe VSF curves rather comprehensively. In what follows we shall conform to the same description mode.

### Numerical experiments on inverting the hydrosol VSF.

According to the present views [11-15], the particle size distribution of the marine suspension can be represented as a sum of two major components, terrigenous and biogenic ones. The components usually have different refraction indices and different slopes of their PSD.

We made the following suppositions within the context of this work. Terrigenous particles have a refraction index of n = 1.15. Their PDS is lognormal with a mode in the vicinity of very small particles (radii of an order of $5\times10^{-4} - 10^{-2}$ μm). Within the optically meaningful range, starting with 0.1 μm, the shape of PDS does not contradict to the shapes of the curves described in [15, 16] by other analytical dependencies.

Particles of biogenic origin have a refraction index of n = 1.05. Their PSD can be described by a function of the Junge type [11] with the exponent ν varying from 2.5 to 4.5 and the initial radius

$r_0$= 1.3 μm. The determination of the limits of the number densities was based on data by Mobley [14] (see his Fig. 3.2).

For the numerical experiments we chose ten distributions. The parameters of these distributions were sampled randomly out of Table 1. The only restriction imposed on the random sampling was that the scattering coefficient corresponding to an individual PSD did not exceed 9.5 $m^{-1}$, the maximum value of the scattering coefficient observed during the LEO -15 Experiment [10].

Table 1. The range of the initial parameter set for hydrosol.

| Component | $N_i$ ($cm^{-1}$) | $a_l$ (μm) | $s_l$ | $v$ |
|---|---|---|---|---|
| 1.Terrigenous | $10^8 - 10^{13}$ | 0.0005 – 0.001 | 0.4 – 0.9 | - |
| 2.Biogenic | $10^3 - 10^5$ | - | - | 1.5 – 4.5 |

From the constructed initial PSD, VSF were calculated by the Mie formulas and then subjected to inversion by the method of mean ordinates. In other words, the inversion procedure was the same as that described for aerosol earlier.

All inversions yielded a similar accuracy. For all initial experimental VSF with errors set at 5%, the inversion error for both components was 13% at worst. For the most part it was less than 5%. For an initial experimental VSF error of 20% the inversion error for the terrigenous component remained approximately within the same limits; the error for the biogenic component increased at most to 20%.

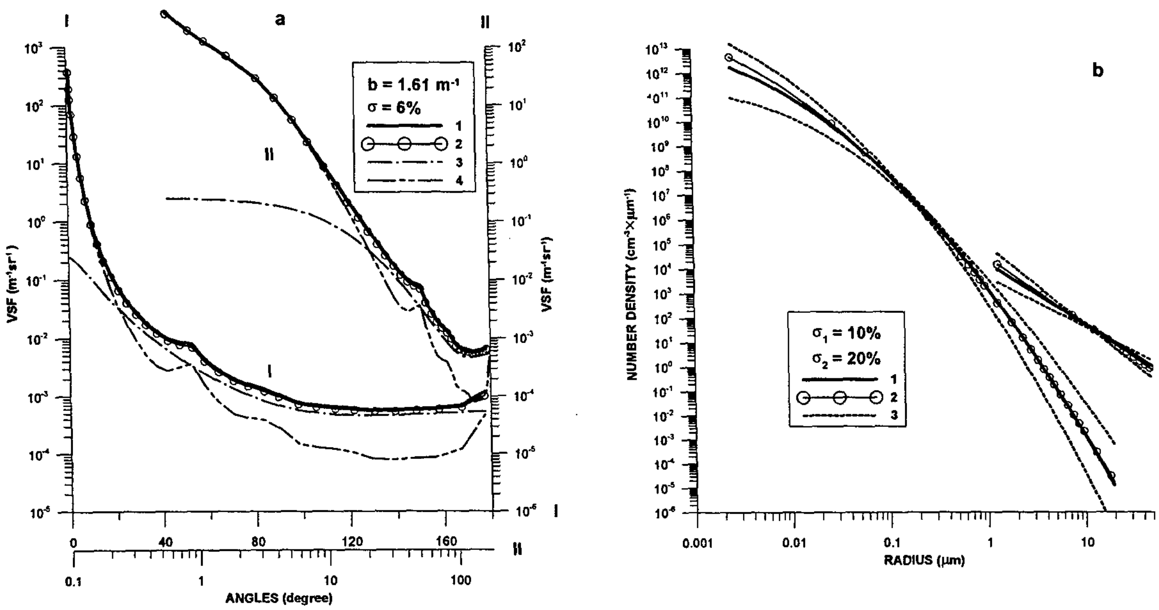


***Fig. 1. Inversion results for a hydrosol model. a, VSF; 1, initial VSF; 2, VSF obtained by inversion; 3, terrigenous VSF; 4, biogenic VSF; b, PSD; 1, initial terrigenous and biogenic components; 2, terrigenous and biogenic components obtained by inversion;***
***3, envelope of all acceptable components of PSD.***
***[It is seen that the inversion accuracy is quite good ]***

Fig.1 demonstrates the inversion results of the numerical experiments for one of the models, with Fig. 1a showing the initial VSF and the reconstructed VSF. The angles are represented at two scales, a linear one (Part I of the figure), and a logarithmic scale (Part II). The same figure indicates the scattering coefficient b and the error σ of VSF obtained by inversion.

Fig. 1b shows the initial PSD and that obtained by inversion. The same figure indicates the inversion errors $\sigma_1$ and $\sigma_2$ for the terrigenous and biogenic components respectively. Lines 3 represent envelopes of all acceptable solutions, that is, of all models whose VSF deviates from the initial VSF by no more than 20% (the limiting measurement error). They show the uncertainty of the inversion of a VSF associated with the indicated experimental error. Although the case demonstrated on Fig. 1 was chosen as the worst case out of 10 samples, it showed nevertheless quite good inversion results.

The measuring scheme with 36 values of VSF proved to be extremely stable. Attempts to artificially displace the parameters of models from the PSDs obtained by inversion and try to perform inversions outside the ranges indicated in Table 1 did not extend the area of acceptable solutions; models constructed outside the above area did not conform with the initial VSF within the limiting error.

**Inversion of measured VSF.**

After considering these encouraging results, we applied the method of mean ordinates to four VSF obtained during the LEO – 15 Experiment [10]. The parameter ranges of the models used in the inversion of these experimental data were taken from Table 1. Notwithstanding the fact that the authors in [10] indicate an experimental error as being equal to 5%, we could not succeed in finding two-component models of this accuracy. Probably for a very turbid waters, the effects of multiple scattering and particle non-sphericity complicate the general picture. The limiting error of the initial VSF employed in this inversion was 35%.

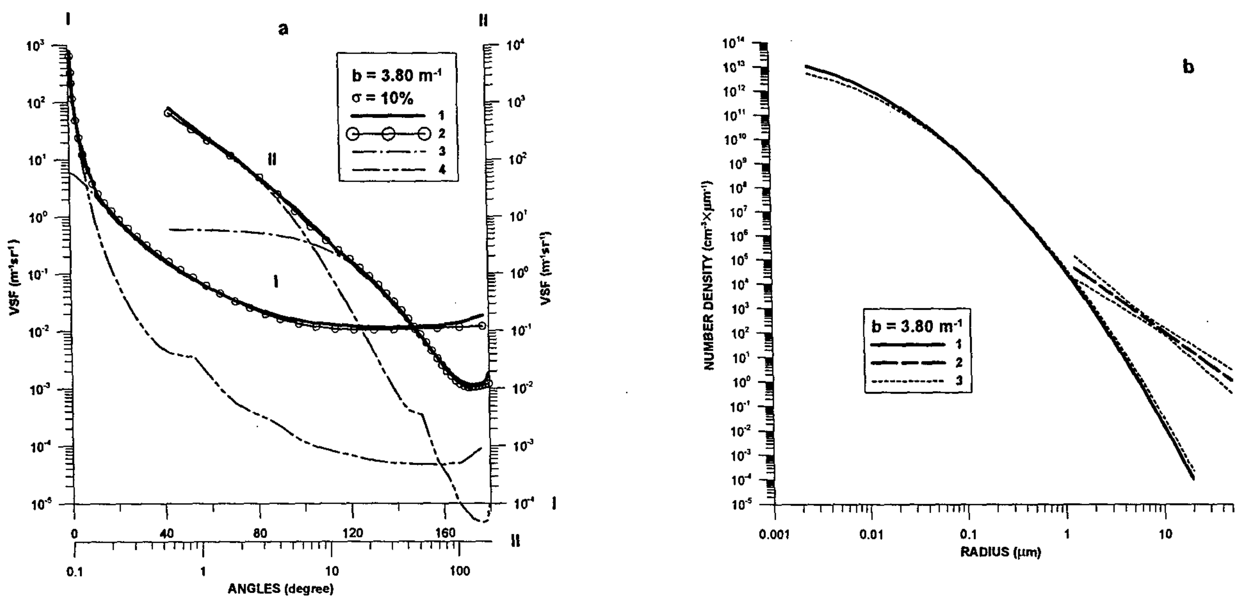


*Fig. 2 Inversion results for an experimental VSF, the scattering coefficient is 3.80 m$^{-1}$. Notations are the same as in Fig. 1.*
*[It is seen that the inversion of experimental VSF yields an optically adequate solution ]*

The result of one inversion is shown on Fig. 2. Fig. 2a shows experimental VSF and VSF obtained by inversion. The average error of VSF calculated from four inversion-derived PSD with respect to the initial VSF was 7%, 10%, 16%, and 20% for appropriate inversions.

Fig. 2b presents most probable solutions for the terrigenous and biogenic components. Envelopes of all acceptable solutions are shown. It turned out that the terrigenous component can be retrieved with a better accuracy than the biogenic one.

In general it can be concluded that the results obtained by inversion of the measured VSF look quite credible. However in the absence of direct PSD observations one can speak only of the optical equivalency of these inversion results.

## RESULTS

- The measuring scheme for oceanic hydrosol VSF at 36 angles proved to be very stable to the inversion process. It insured an unambiguous determination of the area values of the hydrosol particle size distribution function.

- The employment of the method of mean ordinates to the inversion of real VSF obtained during LEO-15 Experiment yields hydrosol PSD optically adequate to the initial data.

## IMPACT/APPLICATIONS

A reliable method for inverting scarce optical data was developed and tested with real experimental data. Its efficiency, resulting accuracy, and validity limits were established. The method was made available for the scientific community. A computer code for the realization of this method is placed on site http://www.coas.oregonstate.edu/people/zolotov/index.html. It is provided with a detailed instruction on its use and by a number of examples on calculations by this method.

## RELATED PROJECTS

Our method for retrieving APSD from optical observations is being used in our NASA-funded project "The Refinement of the Atmospheric Correction Algorithm for Determining the Marine Chlorophyll Concentration from Space".

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## PUBLICATIONS

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